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Studies of film formation and erosion by hydrocarbon injection at the plasma edge of TJ-II

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Abstract

Injection of methane and ethylene at the plasma edge of the TJ-II stellarator has been performed by using an instrumented, mobile limiter. The insertion of the limiter into the plasma leads to enhanced carbon contamination due to the local deposition of hydrocarbon films. The deposition characteristics of these films, their removal by plasma erosion and the spectroscopic signatures of such erosion have been recorded. The relative erosion efficiency by locally injected hydrogen and plasma particles has been compared. The relative yields of photon emission during the deposition (CH, Hα) and erosion (CH) for the different species used is analysed and compared to pure H injection. It is found that ethylene yields only a 15% of Hα photons per injected molecular H atom compared to H_2 fuelling. Also, the ratio of CH/Hα photons delivered upon molecular cracking at the edge is a factor of three higher for ethylene than for methane.
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1. Introduction

Carbon migration in fusion devices represents a hot topic with direct implications in fuel retention, material mixing and lifetime and plasma contamination [1]. To date, this process, which implies the interplay between plasma wall interaction phenomena, atomic physics and plasma transport, is not fully understood, and strong efforts have been devoted to its modelling [2]. One of the key issues is the multi-step characteristics of the transport process, in which the erosion yield of re-deposited material plays a major role. Although much work has been devoted to the understanding of methane and its corresponding radicals, C_2 hydrocarbons are by far less understood. However, an important fraction of carbon release by chemical sputtering in the form of C_2 hydrocarbons may be expected under divertor scenarios [3]. On the other hand, characterization of carbon erosion by its spectroscopic signatures is still challenging, and a significant effort is being devoted to the task at present [4]. In the present work, hydrocarbon fuelling experiments have been performed in ECRH TJ-II plasmas by locally injecting methane and ethylene. H injection is also used for reference. Due to the

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magnetic topology of the puffing location, characterized by strong ripple of the magnetic field, prompt re-deposition of the active species created in the cracking of the corresponding hydrocarbon is to be expected [5]. The edge parameters and their possible change during injection were monitored by atomic beams and Langmuir probes. First, the spectroscopic signatures of the injected molecule were recorded. Particle balance for the injected H atoms indicates that cracking of the hydrocarbons convey a high retention of this species into the created film. The experiments were then focussed on the erosion by the plasma of the deposited films on the limiter. Thus, comparison between erosion of the 'clean' and contaminated carbon limiters allowed the identification of the specific effect of the deposited layer. In addition, the possible enhancement of film erosion near the puffing location was tested in matched discharges. In what follows, an account of these observations and their implication in the understanding of the carbon migration process in edge plasmas is given.

2. Experimental

The TJ-II stellarator has been described elsewhere [6]. For the experiments here reported, ECH plasmas (2 gyrotrons, 2nd harmonic, 250 kW each) were produced. The first wall was fully boronised and He or Ne GD conditioning was run prior to the operation. The vessel and the limiters were kept at room temperature. Hydrogen plasmas were used as the background for the injection of hydrocarbons and hydrogen through a hole located in the middle of a poloidal limiter that can be inserted into the plasma and is controlled remotely, as described in previous works [7]. Gas flows through the inlet are calibrated by expansion into the vacuum vessel. Another limiter, located at 180 toroidally from the gas inlet, is instrumented with Langmuir probes. Two Hα monitors look at the limiters under an identical geometry and they are calibrated with respect to each other. A photomultiplier and an interference filter (1 nm FWHM, centred at 431 nm) are used to collect the CH emission from puffing location through a lens. A set of two photomultipliers and interference filters at 706 and 728 nm are also looking at the injection hole. They are used for the evaluation of possible changes in edge temperature through the line ratio evolution of He atoms, which are eventually injected in a small proportion with the puffing. A CCD camera from a toroidal window (time resolution of ~20 ms/frame) allows for the direct observation of the injection through the limiter. Other edge diagnostics include different types of impurity and particle monitors, a thermal lithium beam and a supersonic He beam. Outgassing of hydrogen after the discharge is evaluated by a differentially pumped mass spectrometer.

3. Results

Pulses of 12–15 ms of methane, ethylene and hydrogen were injected at a fixed time of the discharge, corresponding to the injection of ~4–8×10^{18} particles. The response of some plasma parameters to the injection is shown in Fig. 1 for the three species, H_2 (top), CH_4 (bottom) and C_2H_4 (middle). The location of the limiters corresponds to the nominal LCFS for these shots. As seen, plasma density, local Hα emission and central carbon density (CV) show a more or less significant increase as the species is injected. For the shots displayed in the figure, no significant changes in the edge electron temperature (not shown) were recorded. When comparing ethylene and hydrogen injection, apparent from the figure is the higher increase in local Hα emission for the hydrogen case and the higher relative increase of the central carbon emission for ethylene injection. Highly localized emission near the inlet at the limiter was observed also by the CCD camera for both cases but it was clearly more intense in the H_2 case. Table 1 displays the comparison of density and neutral hydrogen emission upon the injection of either molecule (C_2H_2 and H_2). As seen, a much lower fuelling efficiency for ethylene is deduced, in spite of its much higher electron/molecule content. This is also true for the increase of local Hα emission, in spite of the higher H/molecule ratio of ethylene. For this species, the relative Hα photon yield per injected H atom is only a 15% that of hydrogen. If methane and ethylene are compared respect to their spectroscopic signatures, it is found that the ratio of CH/Hα emission intensities is a factor of three higher for the case of ethylene at the typical edge conditions of the plasma edge, $T_e = 30$ eV and $n_e = 2 \times 10^{12}$ cm^{-3}. The outgassing of hydrogen after the discharge, when compared between fuelled and non-fuelled shots, also points to a lower release of free H atoms upon the cracking of the hydrocarbon in the plasma. All this information can be analysed under the view of the prompt deposition of

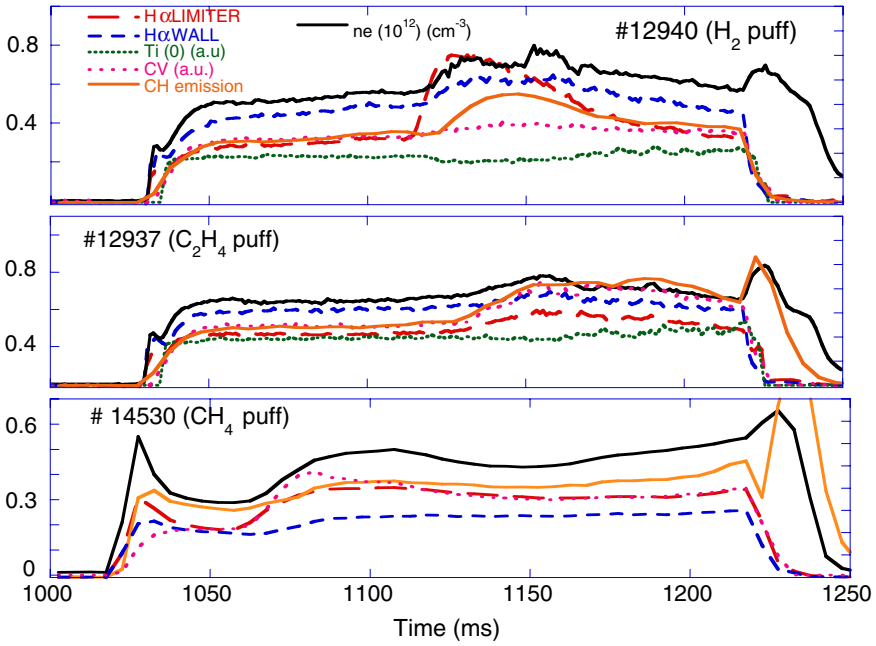

Fig. 1. Injection of hydrogen, ethylene and methane in the TJ-II plasmas.

Table 1
Comparative yield of H atoms and electrons for the injection of ethylene and hydrogen in the TJ-II edge through a limiter

	Ethylene	Hydrogen
Electron/molecule	14	2
Mol/pulse	7×10^{18}	8.7×10^{18}
Densityincrease/pulse (total electrons)	1.2×10^{18}	1.5×10^{18}
H/molecule	4	2
Hα increase/pulse (a.u.)	3	10
H outgas/H in	0.10	0.25

carbon layers with high H content when ethylene is fed into the plasma.

The topic of local contamination by the injection of hydrocarbons is specifically addressed in the experiments of limiter insertion shown in Fig. 2. Ethylene was injected as 15 ms pulses during a radial scan of the limiter position in two different configurations. In each scan, the symmetric limiter was kept at the location of the nominal LCFS. Thus, limiter C (the one that carries the gas inlet) was gradually inserted from the normalized minor radius $r = 1$ up to 25 mm inside the LCFS ($r \sim 0.8$) in discharges <13 575. From 13 576 to 13 582, the reverse was made, i.e., limiter A was inserted while limiter C remains at the LCFS position. Data shown in parts (a) and (b) of the figure refer to the parameter value before the pulse is produced ($t <$ 1120, Fig. 1). As seen in the figures, local enhancement of recycling at the limiter that is inserted is observed. However, only a small decrease of particle fluxes in the opposite location is simultaneously recorded. It must be kept in mind that the total displacement of the limiter is more than twice the corresponding density decay length of the SOL (~1 cm) of this type of plasmas. As ethylene is being puffed during the whole scan, chances of creating a local amorphous carbon layer near the injection point exist. Evidence of this is shown in the systematic increase of the plasma carbon content as limiter C is inserted shot by shot Fig. 2(b). Conversely, a constant value (although higher than the initial one) of this plasma impurity is found when the carbon limiter A is moved inside the LCFS, thus indicating that simple erosion of the graphite limiter is not responsible for the enhancement. Fig. 2 bottom shows the fuelling effect of the injected ethylene. As seen, a fairly constant value is reached for all limiter settings and only for the innermost locations of the limiter (>2 cm in) an enhanced effect takes place. The value of this, however, represents only a 2% of the available electrons in the pulse.

The formation and erosion of films created by hydrocarbon injection was specifically addressed in the experiments corresponding to Figs. 3 and 4.

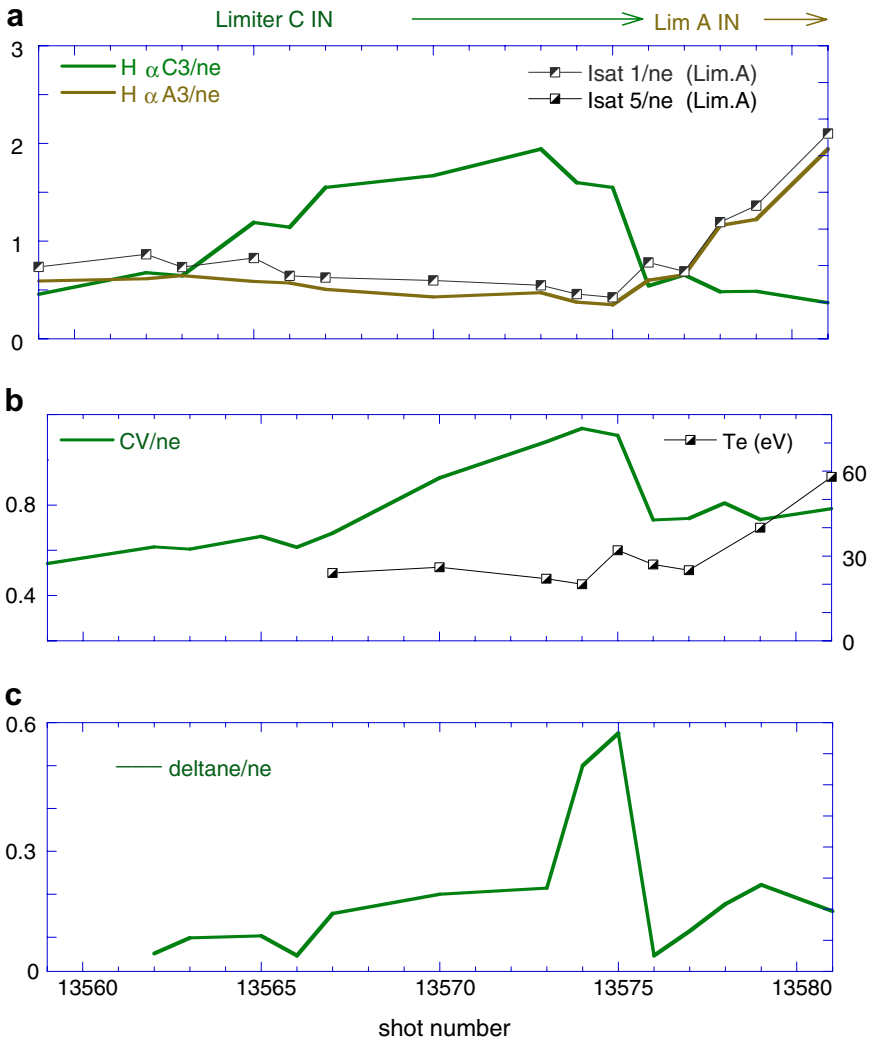

Fig. 2. Effects of limiter insertion in the plasmas depending on hydrocarbon deposition. Lim C, contaminated. Lim A, clean.

First, a single pulse of the hydrocarbon species (2–4×10^{18} mol) was injected through the limiter into the plasma. Then, the gas was replaced by hydrogen and a series of repetitive pulses were run. The process was repeated at several positions of the limiter and for both hydrocarbons. Alternatively, hydrogen was fed into the plasma through a valve far from the observation region, so that no extra neutral density increase, aside from that expected from local recycling, was foreseen. Density matching was attempted when possible. In Fig. 3, the time behaviour of some relevant signals is shown for the erosion of ethylene films by plasma and by local puffing for those created from either of the hydrocarbons. Also displayed are the emission lines from He atoms from wall recycling, implanted during the GDC conditioning. An average Te value of 50–60 eV in the full observation zone is deduced. Independent measurements with intentionally He contaminated H injection showed that no significant changes of this parameter take place during H puffing. Although absolute different quantities of gas are injected in each case, it is worth noting two important features. First, the ratio of enhanced CH emission to that of local Hα is independent of the type of molecule used as precursor of the film. This is in agreement with the expected independence of the type of film from type of precursor. Secondly, and contrary to simple expectations, a higher erosion efficiency by plasmas fed away from the limiter

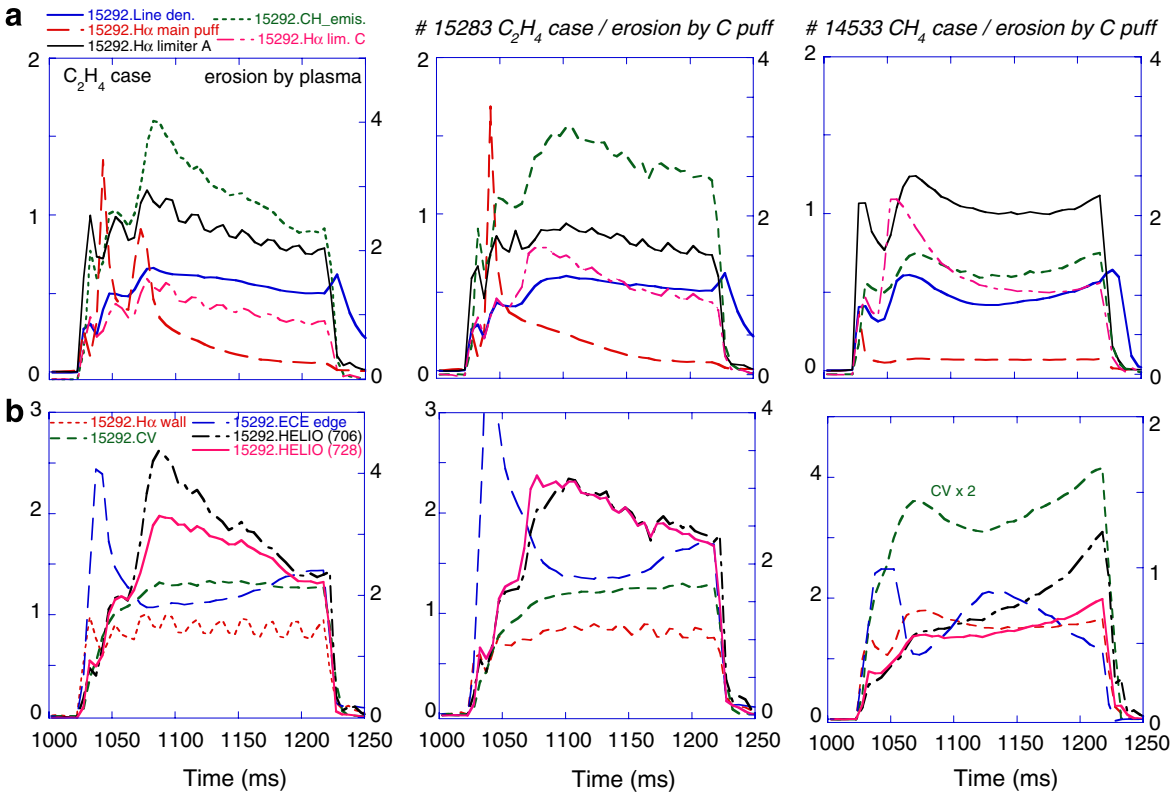

Fig. 3. Erosion of hydrocarbon films by plasma particles and local puffing. Examples for ethylene and methane film precursors are shown.

is also observed. However, care has to be taken in the interpretation of this apparent contradiction. Certainly, enhanced atomic H density should be expected near the injection port, leading to chemical sputtering at the energies characteristic of Frank–Condon atoms. Previous experiments [7] indicate that physical sputtering is the major contribution to carbon contamination in TJ-II. The low temperature of the limiter and the relatively high energy of the escaping particles for these, limiter plasmas would be responsible of that. However, the simplest explanation for the observed behaviour could be pure experimental, and due to the contribution to the recorded enhanced emission of other parts of the machine contaminated by the injection that would mask the expected effect. This is more clearly seen in Fig. 4. The full history of one ethylene injection run is shown. Vertical lines indicate the time when a new layer is created by injection of ethylene. Note that two locations of the limiter were tried, and both types of erosion scenarios were explored. In the top figure, the shot by shot evolution of the incremental and background CH/Hα emissions are plotted. Also for reference, the incremental values for freshly conditioned limiter are shown. A systematically higher value of this parameter is seen in the contaminated limiter in all cases. Also, no apparent evolution of this ratio in consecutive 'etching' discharges can be detected. If some film is still remaining before the next deposition, no significant changes of the emission signatures during the next ethylene injection happen within the scattering of the data. The ratios are systematically higher for plasma etching (as opposed to local puffing) and for deeper insertion, as expected from pure physically sputtered films. In the bottom part, the continuous evolution of density normalized CH and CV emissions is displayed. As seen, a slowly rising background is seen, in agreement with the expected global contamination of the full wall during the experiment. In fact, mass spectrometry indicates that only a 50% of the injected molecule is actually cracked in the plasma, therefore having a high probability of deposition in remote areas of the wall. The parallel trends of CH and central carbon can be interpreted in a first approach as a constant contribution of chemically sputtered vs. physically sputtered (dominant) carbon source in TJ-II.

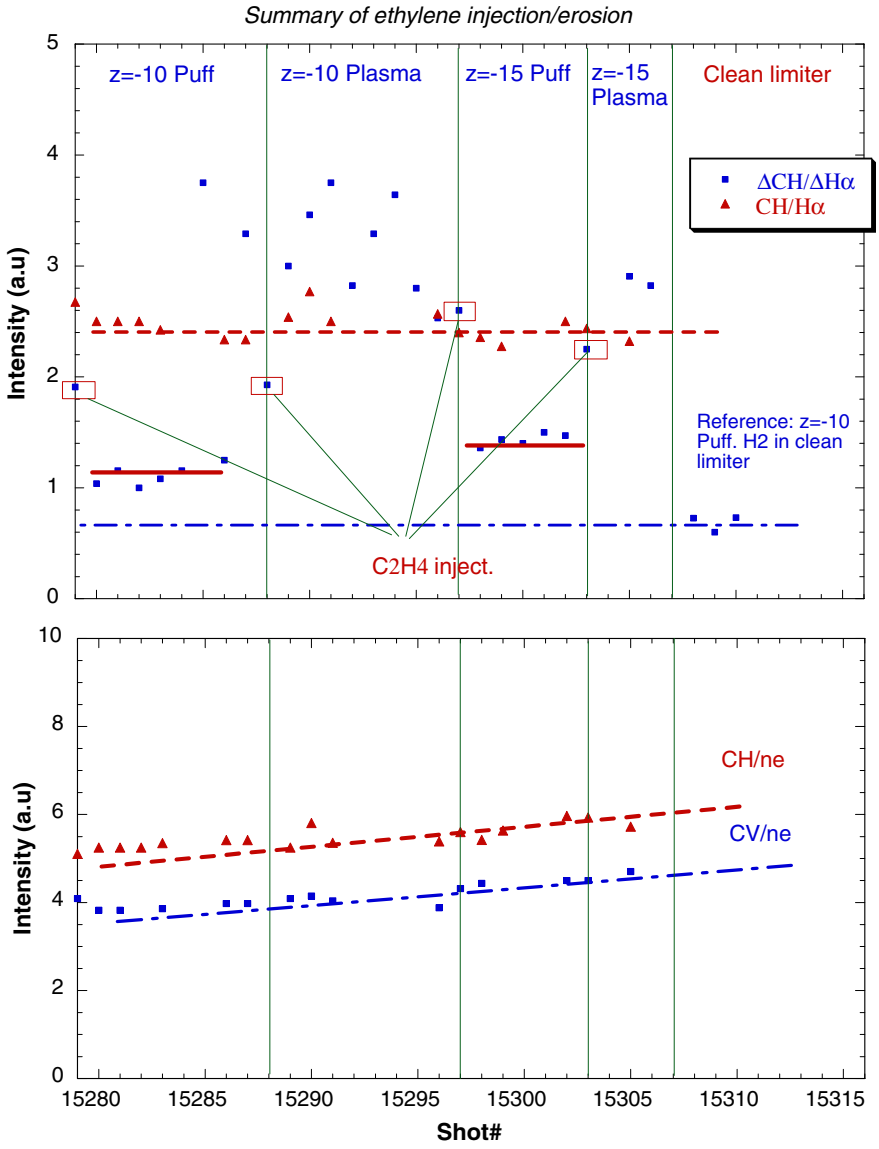

Fig. 4. Time history of deposition and erosion of ethylene injection in the plasma at different locations of the limiter. Examples of plasma erosion and local puffing erosion, together with the behaviour of a clean limiter, are shown.

4. Summary and conclusions

Injection of methane and ethylene at the plasma edge of the TJ-II stellarator has been performed by using an instrumented, mobile limiter. The insertion of the gas-injection limiter into the plasma leads to enhanced carbon contamination, as a consequence of the local deposition of hydrocarbon films.

Erosion of the deposited films by the plasma and by local puffing has been compared. The direct data indicate that plasma erosion is more efficient than local puffing for the removal of the films. However, the contribution of other parts of the vessel also contaminated could mask the expected enhancement due to FC and CX neutrals.

Ethylene yields only a 15% of Hα photons per injected molecular H atom when compared to H_2 fuelling. Also, the ratio of CH/Hα photons delivered upon molecular cracking at the edge is a factor of three higher for ethylene than for methane under the edge conditions (50 eV, 2×10^{12} cm^{-3}) of the plasmas under study.

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